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The X-ray Spectrum of the Soft Gamma Repeater 1806-20

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ABSTRACT

Soft Gamma Repeaters (SGRs) are a class of rare, high-energy galactic transients that have episodes of short (~ 0.1 sec), soft (~ 30 keV), intense (~ 100 Crab), gamma-ray bursts. We report an analysis of the x-ray emission from 95 SGR1806-20 events observed by the *International Cometary Explorer*. The spectral shape remains remarkably constant for bursts that differ in intensity by a range of 50. Below ~ 15 keV the number spectrum falls off rapidly such that we can estimate the total intensity of the events. Assuming that SGR1806-20 is associated with the supernova remnant G10.0-0.3 (Kulkarni and Frail, Murakami *et al.*), the brightest events had a total luminosity of 1.8×10^{42} erg sec^{-1}, a factor of 2×10^4 above the Eddington limit. A third of the emission was above 30 keV. There are at least three processes that are consistent with the spectral rollover below 15 keV. (1) The rollover is consistent with some forms of self absorption. Typical thermal

temperatures are ~ 20 keV and require an emitting surface with a radius between 10 and 50 km. The lack of spectral variability implies that only the size of the emitting surface varies from event to event. If the process is thermal synchrotron the required magnetic field might be too small to confine the plasma against the super Eddington flux. (2) The low energy rollover could be due to photoelectric absorption by 10^{24} Hydrogen atoms cm^{-2} of neutral material with a cosmic abundance. This assumes a continuum similar to thermal bremsstrahlung with a temperature of ~ 22 keV. The material is most likely to be associated with the object as circumstellar matter a few A.U. from the central source rather than foreground clouds or directly at the site of the energy release. (3) Emission in the two lowest harmonics from a 1.3×10^{12} Gauss field would appear as Doppler broadened lines and fall off rapidly below 15 keV.

Subject Headings: Gamma-Rays: Bursts – X-Rays: Bursts – stars: individual (SGR1806-20)

1. INTRODUCTION

Mazets and Golenetskii (1981) first suggested that short events comprise a separate class of gamma ray bursts (GRBs) based on soft events from GRB790305 (the "March fifth" event), GRB790107, and GRB790324 as well as several hard events. Two of these sources had soft repetitions: SGR790305 (Mazets and Golenetskii 1981; Golenetskii, Iiyinskii, and Mazets 1984) and GRB790324 (Mazets, Golenetskii, and Guryan 1981). With the discovery of $\sim$ 110 soft and short recurrences from SGR790107 (Laros *et al.* 1986, 1987; Atteia *et al.* 1987), this class has been called the Soft Gamma Repeaters (SGR). Norris *et al.* 1991 has reviewed their properties. The sources are designated SGR followed by the location. Thus, GRB790305 (March fifth) is also known as SGR0526-22, GRB790107 is known as SGR1806-20, and GRB790324 is SGR1900+14. These sources are thought to form a separate class of events with different physics than the classic GRB. Other short GRBs (i.e., less than 1 second in duration) have hard spectra like the longer classic GRBs and are probably just extreme examples of a bimodal duration distribution for classic GRBs (Klebesadel 1992, Kouveliotou *et al.* 1993b). Recently, the Burst and Transient Experiment (BATSE) has observed some activity in both SGR1900+14 and SGR1806-20 (Kouveliotou *et al.* 1993a, Kouveliotou *et al.* 1994).

The Soft Gamma Repeaters have distinct properties from those of other classes of high energy transients. Their typical photon energy is 30 keV whereas the x-ray bursters have typical energies of 3 keV and the classical GRBs have typical energies in excess of 300 keV (see *e.g.,* Band *et al.* 1993). The classical GRBs often have complex time histories lasting from less than a second to more than 1000 seconds (Klebesadel, 1992, Fishman *et al.* 1993) and the x-ray bursters have simpler time histories with a sharp rise and a decaying tail lasting about 30 seconds. In contrast,

time histories of SGR rise sharply and fall with the whole event lasting on the order of 0.1 second (Atteia *et al.* 1987). Classic GRBs do not seem to repeat whereas x-ray bursters do repeat with a characteristic pattern (Lewin and Joss, 1983). The SGR do not have any discernible pattern in the repetitions (Laros *et al.* 1987).

The bright March fifth event has been studied in great detail. A number of interesting characteristics were discovered that have helped guide the study of soft gamma repeaters. Foremost, there is an 8 second periodic emission for more than 200 seconds after the initial burst (Mazets *et al.* 1979). If the pulsations are due to stellar rotation, then such a period strongly suggests a neutron star origin. The March fifth error box is extremely small (0.1 arcmin^2) (Cline, *et al.* 1982) and occurs in the direction of the supernova remnant N49 in the Large Magellanic Cloud (Evans *et al.* 1980). The distance to N49 (55 kpc) implies a huge energy release in the initial spike ($\sim 10^{44}$ ergs sec^{-1} above 30 keV). Such a release of energy on a neutron star would be super-Eddington by a factor of 10^6, raising doubts that the object could be as far away as implied by the supernova remnant in its error box.

SGR1806-20 is located within 7 degrees of the galactic center (Atteia *et al.* 1987) and the third known burster, SGR1900+14, is in the galactic plane (Mazets, Golenetskii, and Guryan 1979) Therefore, a population I distribution has been suggested (Laros *et al.* 1986, Kouveliotou *et al.* 1987). The recent detection of a burst in a small error box centered on the supernova remnant G10.0-0.3 (Murakami *et al.* 1994) confirms the earlier association suggested by Kulkarni and Frail (1993). The radio characteristics of G10.0-0.3 provides a distance estimate of 17 kpc for SGR1806-20 (Kulkarni and Frail, 1993).

2. INSTRUMENTATION

Fortunately, SGR1806-20 was located in the ecliptic plane, and thus, was always

within the field of view of the UCB/Los Alamos experiment on the *International Cometary Explorer* (ICE, see Anderson *et al.* 1978). This experiment provided nearly continuous coverage from late 1978 to 1986, and all known bursts from SGR1806-20 were detected by ICE. The experiment consisted of a proportional counter and a scintillator which together gave spectral information between 5 keV and 2 MeV. The ICE experiment yielded excellent data in which to search for spectral variability and to determine the overall spectral shape of SGR1806-20. Laros *et al.* (1987) reported 111 bursts believed to be from SGR1806-20. Later, a more sensitive search found 23 more events in ICE data (Laros *et al.* 1990), and since the 111 bursts showed a power law luminosity function, it is likely that more existed below the sensitivity of the instrument. Ulmer *et al.* (1993) cataloged all of the ICE SGR1806-20 events. We studied a subset of the original 111 bursts. Some of the events were rejected because of background variations (most likely due to solar activity) which made estimating the signals uncertain, and a few events were not used because the instrument had been commanded to a nonstandard gain. The data for a few events are currently unavailable. In all, 95 of the original 111 were judged suitable for spectral analysis. These bursts had backgrounds that could be fit to within the statistics with either a constant or linear function. The uncertainty due to the background fitting was propagated into the error bars quoted in this paper.

ICE viewed these bursts with both a collimated proportional counter (PC) which functioned in the 5 to 14 keV range and a collimated scintillator counter (SC) which allowed measurements from 26 keV to 2 Mev. The PC had an effective are of ~ 1.5 cm^2 and six energy channels: PC1 (5.0 to 6.0 keV), PC2 (6.0 to 7.0 keV), PC3 (7.0 to 8.5 keV), PC4 (8.5 to 10.0 keV), PC5 (10.0 to 12.0 keV), and PC6 (12.0 to 14.0 keV). The SC had an effective area of ~ 22 cm^2 and twelve energy

channels; however, the bursts from SGR1806-20 are so soft that they rarely show a net signal beyond the fifth scintillator energy bin (SC5). The third SC channel (SC3) stopped operating in March of 1983, before the source became extremely active. Thus, usually there are 3 or 4 SC channels with net signals: SC1 (from 25.9 to 43.2 keV), SC2 (43.2 to 77.5 keV), SC4 (121 to 154 keV) and SC5 (154 to 236 keV). The SC6 channel covered from 236 to 320 keV. In our fitting, we used 11 energy channels, 6 from the PC and 5 from the SC. Time samples were continuously taken at half second intervals for most of the energy channels. Two energy channels, PC5 and PC6, had time samples of four seconds.

3. SPECTRAL VARIABILITY

A key characteristic of SGRs is the similarity between different bursts from the same source. Differences among the spectra of various bursts from SGR1806-20 are hard to discern. The bright bursts from SGR1806-20 observed by *Prognoz 9* appear to have a common spectral shape above 30 keV (Atteia *et al.* 1987). The spectra from five different *Prognoz 9* bursts were consistent with optically thin thermal bremsstrahlung with a single temperature even through the total intensity of the different bursts in that analysis varied by a factor of four. In addition, the *Solar Maximum Mission* (SMM) resolved one burst from SGR1806-20 into two time samples with spectral information above 30 keV and found no indication of spectral evolution (Kouveliotou *et al.* 1987). However, significant variations have been observed within the main peak of the March 5th event (Fenimore *et al.* 1981).

These previous studies used the strongest SGR1806-20 events. The 95 ICE events cover a dynamic range of 50 and allow a more sensitive search for correlations between brightness and spectral shape. Figure 1 shows a hardness ratio of counts (SC2 to SC1) plotted as a function of estimated fluence for the 95 SGR1806-20

events used in this study. The fluence is based on the sum of SC1 and SC2 normalized by the integrated spectral shape of the strongest bursts. Error bars on the estimated fluence are excluded from the plot but were used in the analysis. Fitting a constant to the 95 hardness ratios yielded a χ^2 of 164 with 94 degrees of freedom. Fitting a linear function yielded a somewhat better χ^2 (145, 93 degrees of freedom). Neither fit has an acceptable χ^2. The solid line in Fig. 1 shows the best fit linear function. The high χ^2 of the fits seems to be attributed to scatter about a typical hardness ratio rather than being due to some nonlinear trend in hardness with fluence. This scatter could be due to systematic effects. For example, there are posts within the SC collimator which could partially intercept the beam from some events depending on the rotation angle of the satellite at the time of the burst. Alternatively, the scatter could be due to intrinsic variations within the source. If so, this would be the first evidence that the spectra of SGR1806-20 can vary from burst to burst. We want to emphasize that the variation is very small, the linear fit only varies by 30% over a dynamic range of 50. If the changes in fluence were due to blackbody emission with changing temperature but constant area, the resulting hardness ratios would vary by ~ 12. Clearly, some process is regulating the spectrum and maintaining a constant shape. To match the hardness variations seen in the linear fit would require the temperature of a thermal bremsstrahlung continuum to change only from 19 to 28 keV. This is a small range of spectral shape compared to classic gamma ray bursts which show variations from 100 to 600 keV and variations within individual events (Band, *et al.* 1993). This relative constancy of the hardness ratios over such a large range of intensities is a feature that a successful model must explain. We have also searched for a correlation between hardness and the time of occurrence of the bursts and found nothing obvious.

Another potential correlation would be between the x-ray observations (with

the PC) and the gamma-ray observations (with the SC). We find that the hardness ratios between 26 to 78 keV (SC1+SC2) and 10 to 14 keV (PC4+PC5+PC6) are consistent with a constant spectral shape. We cannot place rigorous constraints on this ratio because of low statistics in the PC channels. We would notice a difference if the ratios were correlated between intensity and varied by more than a factor of 2 over the range of observations. However, comparing Figs. 5, 6, and 7 shows a trend that the x-ray emission grows relative to the gamma-ray emission for weaker bursts.

4. X-RAY SPECTRUM OF SGR1806-20

Previous spectral analyses of bursts from SGR1806-20 have been limited to above 30 keV (Mazets, *et al.* 1982, Atteia *et al.* 1987, Kouveliotou *et al.* 1987) except for the ICE PC observations of GRB790107 (Laros *et al.* 1986). Laros *et al.* found that the PC observations showed a deficiency below 30 keV relative to optically thin thermal bremsstrahlung, but the signal was not strong enough to determine whether or not the spectrum rolled over and decreased at low energy. The ICE PC observed SGR1806-20 down to 5 keV. The x-ray diffuse background was dominant so only the strongest events could be studied individually. To search for spectral variability, we ordered the events by the fluence in SC1 plus SC2 since fluence is usually correlated with signal-to-noise. We then summed together events to obtain statistically significant spectra. It was necessary to group together the strongest event and the third strongest event. These two events occurred one second apart on November 16, 1983 and were added together not because of weak statistics, but because the PC5 and PC6 temporal samples encompassed both bursts.

We fit different spectral shapes to the data by folding the models through the instrument response matrix and varied the model until the best parameters were

found. It is clear from the brighter events and the summed weaker events that the number spectrum is no longer monotonically increasing below 15 keV; there is a strong rollover in the x-ray portion of the spectrum. All models without rollovers gave unacceptable χ^2. This includes thermal bremsstrahlung which had been used exclusively above 30 keV in previous work as well as power laws, exponentials, and unsaturated inverse Comptonization. We tried many different types of spectral shapes to determine which physics might be applicable. The models that produce rollovers can be grouped into three classes: (1) self absorption (blackbody or various functions connected to a Rayleigh-Jeans law), (2) photoelectric absorption by neutral material in molecular clouds or in a circumstellar region, and (3) edges to emission processes such as cyclotron radiation.

Figures 2 through 7 show fits to various spectra for SGR1806-20. The upper right hand corner gives the events that were used. For example, 831116-G means the 7^{th} event on Nov 11 1983. The number in parenthesis gives the event's ranking in fluence (*i.e.*, 1 means it was the strongest event seen by ICE). The UT for these events are given in Table I and Ulmer *et al.* (1993) list all the events for each day and their intensities. In some cases the event was split between two 0.5 sec samples in which case we only used the sample with the strongest signal to avoid reducing the signal-to-noise by including a 0.5 sec sample with only a small fraction of the total signal. The duration for the purpose of converting counts to photon sec^{-1} was taken to be the duration of the spectral sample (0.5 sec); their actual durations are listed in Table I. For these reasons, the area under the curves will not necessarily be the total intensity of the event as listed in Table I. Shown in each figure are spectral fits for blackbody (BB), thermal bremsstrahlung merged with a blackbody (TB-BB), a power law merged with thermal bremsstrahlung (TB-PL), and thermal bremsstrahlung with photoelectric absorption by neutral material with a cosmic

abundance (TB-PE). The vertical scale corresponds to the blackbody fit and each of the other spectra have been displaced by a factor of 10 to improve visibility.

The solid curves in the figures are the best fit number spectra (photons sec^{-1} cm^{-2} keV^{-1}). The data points with error bars are not measurements of the number spectrum but rather give the residuals between the observed counts and the counts obtained from folding the best fit spectrum through the response matrix. The vertical error bars represent $^{+}_{-}1\sigma$ and the distance from the horizontal central bar to the number spectrum is the residual for that energy channel in units of 1σ. The length of the horizontal central bar gives the width of the energy loss bin. This representation of the spectrum is "obliging" (Fenimore, Klebesadel, and Laros, 1983, Loredo and Epstein, 1989) in that the data points will move to agree with whatever spectral shape is assumed since what they actually represent is the difference between the observed and the model. This obliging nature is intrinsic to detectors (such as the PC and SC) that do not have a δ function response to monoenergetic photons or have strongly varying efficiency.

To avoid confusion, SC4, SC5, and SC6 are only shown for the blackbody fits and only if they are positive. These points have poor statistics and are particularly obliging.

4.1. *Blackbody*

A natural explanation for any spectrum that rolls over is that it is optically thick self absorption which often approaches a blackbody spectrum. A blackbody spectrum also has the key advantage that a distance can be estimated with only an assumption concerning the size of the emitting region. A blackbody number spectrum can be expressed as

$$\phi_{BB}(E) = \frac{0.008284E^2\Psi}{e^{E/kT} - 1} \tag{1}$$

in photons keV^{-1} cm^{-2} sec^{-1} where kT is the temperature (in keV) and Ψ has units of (km/kpc)^2. Figures 2 though 4 show the blackbody fits for the four strongest events individually (with the first and third strongest events combined because PC5 and PC6 were not temporally resolved). The two blackbody free parameters are the temperature (~ 9 keV) and Ψ (~ 30 km^2 kpc^{-2}). In Table II, the errors for the temperature are $\pm 1\sigma$ and are found from where χ^2 changes by 1, appropriate for the range of a single interesting parameter (*cf.* Lampton, Margon, and Bowyer 1976). The "Prob" in Table II is the probability that the χ^2 would be as large as observed by random chance, considering the number of degrees of freedom. Individually, each burst can be fit with an acceptable χ^2 (see Table II), although other models with one or two more free parameters have substantially smaller χ^2. Furthermore, in each fit there appears a trend where the spectrum is steeper below 15 keV than expected for a blackbody (see Fig. 2-4). Combining the four strongest events together (Fig. 5) gives an unacceptable χ^2 (24.7 with 9 degrees of freedom). This large χ^2, due to the low energy steepness of the data, is not caused by variations in the free parameters from event to event since the results of variations in temperature on the composite blackbody spectrum can only be to broaden it. This trend of the blackbody producing the largest χ^2 continues when we add together the 5^{th} to 14^{th} and the 15^{th} to the 40^{th} events (Fig. 6, 7). These large χ^2 are not due to variations in the parameters (which would invalidate the combining of different events). The other model fits show that the spectral shape remains remarkably constant. Figure 1 also argues against a blackbody fit since to maintain a hardness ratio as flat as that of the linear fit to figure 1, the emitting area must coincidently vary by a factor > 15 while the temperature remains nearly constant. We conclude that blackbody can be rejected as the explanation for the low energy rollover seen in the PC data.

4.2. *Thermal Bremsstrahlung - Blackbody*

Rejecting the blackbody shape does not necessarily mean that the rollover is not due to self absorption. To produce a blackbody spectrum, the plasma must be optically thick at all energies. The plasma could be optically thick at low energy and thin at high energies. For free-free absorption with little electron scattering, the spectrum has the form:

$$\phi_{TB-BB}(E) = \phi_{BB}(E)\{1 - e^{-(\phi_{TB}(E)/\phi_{BB}(E))}\} \tag{2}$$

Where, ϕ_{TB} is the optically thin thermal bremsstrahlung continuum,

$$\phi_{TB}(E) = 1.4 \times 10^{-50} n_e^2 l \ \Psi \ E^{-1}(m_e c^2/kT)^{1/2} \ e^{-E/kT} \tag{3}$$

where n_e is the electron density (cm^{-3}) and l is the thickness of the emitting region (cm). This form gives an acceptable fit to the data with $kT \sim 20$ keV and $\Psi = 13.8 \ \mathrm{km}^2 \ \mathrm{kpc}^{-2}$ for the strongest events (see Table II). However, the thermal bremsstrahlung process seems unlikely as the explanation for the high energy spectrum since $n_e^2 l$ is only $1.1 \times 10^{51} \ \mathrm{cm}^{-5}$ and yet the plasma should be optically thin to Thompson scattering ($n_e l < 10^{24} \ \mathrm{cm}^{-2}$). Although thermal bremsstrahlung has been used in fits of SGRs as the continuum above 30 keV (Mazets *et al.* 1982, Atteia *et al.* 1987), it is only characteristic of the shape of the continuum and is not necessarily the actual mechanism. What the TB-BB spectral fit demonstrates is that the low energy rollover could be a self-absorbed Rayleigh-Jeans spectrum even though blackbody is unacceptable over the whole energy range. The 1σ error bars on the temperature assume a single interesting parameter.

4.3. *Thermal Bremsstrahlung - Power Law*

To explore further what slopes below $\sim$ 15 keV are allowed we have fit a power law connected to thermal bremsstrahlung. There were four free parameters: the slope of the power law (α), the connection energy (E_c), the thermal bremsstrahlung temperature (kT), and an overall scale factor. If α is 1 then this formulation could be considered a crude Rayleigh-Jeans law with a discontinuity at the peak where the formula abruptly switches from a positive to a negative slope. The slope below 15 keV is typically found to within $\pm$0.5. The best fit slopes vary from 0.2 to 1.5 with an average near 1.0. In the fourth strongest event (Fig. 4) the χ^2 surface had 2 local minima. The curve labelled TB-PL had a χ^2 of 10.0 and the one labelled TB-PL2 had a χ^2 of 11.1; both should be considered acceptable. The rather different functional forms that can fit the same data demonstrate how obliging the data can be when the statistics become poor. The disparity seen between TB-PL and TB-PL2 was a consideration in our decision to analyze only the first four events as individuals and to combine weaker events together to obtain sufficient statistics. The 1σ error bars on the power law index assume a single interesting parameter. Note from Table II that the derived thermal bremsstrahlung temperature ($\sim$ 22 keV) is lower than earlier reports from *Prognoz 9* (40 keV, Atteia *et al.* 1987) and SMM (30 keV, Kouveliotou *et al.* 1987).

4.4. *Thermal Bremsstrahlung - Photoelectric Absorption*

The rollover in a spectrum may be caused by neutral photoelectric absorption which at these energies is dominated by iron absorption. Photoelectric absorption is a strong function of energy and can therefore produce a rapid rollover. We used Morrison and McCammon (1983) for our calculation of the absorption which is based on cosmic abundances. An distinctive feature of an absorption spectrum in this energy range is an iron edge, but unfortunately, the sensitivity and energy

resolution in the PC channels is not enough to detect the iron edge with certainty. Using a thermal bremsstrahlung continuum (Eq. 3) gives a best fit value for N_H of 1.1×10^{24} hydrogen atoms cm^{-2} and kT $\sim$ 22 keV. The normalization of the thermal bremsstrahlung gives $n_e^2 l \Psi = 1.4 \times 10^{52}$ cm^{-5} km^2 kpc^{-2}. Both the temperature and column density are considered interesting parameters so the 1σ error bars in Table II are based on changes in χ^2 of 2.3. Within the statistics, all samples gave the same column density. Such absorption is likely to be circumstellar and, therefore, rather constant. Even a single example inconsistent with the derived column density would be an argument against absorption being responsible for the rollover. We have therefore checked individually all of the 20 strongest events and found no example that could not be fit by 1.1×10^{24} cm^{-2}. This density is too high for molecular clouds. It is possible that circumstellar material could have an appropriate column density. GX301-2, for example, is in an accreting binary that has a column density over 10^{24} cm^{-2}. (White and Swank 1984). Ejected surface material is another way to provide the matter and is particularly tempting to consider since the source is super Eddington.

The huge photon flux from the SGR threatens to ionize a plasma near the source faster than it can recombine. Assuming the thermal bremsstrahlung shape used in the TB-PE fit (Fig. 2) extends down to at least 5 keV, then $\sim 9 \times 10^{40}$ erg above 5 keV were absorbed in the 1.1×10^{24} H cm^{-2} material. If each ionizing photon is 8 keV, the number of iron-ionizing photons, n_γ, is $\sim 7 \times 10^{48}$. Events 831116-G and 831116-H occurred within one second and there is no indication that the absorbing material was any different for the second event. The absorption is dominated by k-shell ionization of the iron which makes up only a small fraction of the material. The absorption would be turned off only if the iron is completely stripped and if recombination is insufficient to replenish the k-shell electrons. The total

recombination coefficient for iron, $\alpha_{Fe}(kT)$, is approximately $2\times10^{-11}(kT)^{-1/2}$ cm^3 sec^{-1} where kT is the temperature in keV of the electrons (Kaplan and Pikelner, 1970). The number of times that an iron atom can recombine per sec if it is constantly being ionized is $n_e\alpha_{Fe}$ where n_e is the electron density. To allow most of the iron to have filled k-shells within 1 second, the number of ionizations and recombinations per cm^2 must be larger than the number of ionizing photons per cm^2, that is

$$N_{Fe}\big(I_{Fe} + n_e\alpha_{Fe}\big) \gg \frac{n_\gamma}{4\pi R_a^2}$$

where R_a is the radius of the absorbing material and I_{Fe} is the initial number of electrons per iron atom. From the cosmic abundances of Morrison and McCammon (1983), the column density of iron, N_{Fe}, is 3.6×10^{19} cm^{-2}. (Note that the data effectively constrains N_{Fe} rather than N_H.) Using $n_e \sim N_H/R_a$ and $I_{Fe} \sim 20$, one finds that R_a must be at least a few A.U. If the material is iron rich, N_{Fe} remains the same since it is the amount of material necessary to provide the low energy rollover in SGR1806-20, only N_H (and n_e) is reduced. As a result, R_a is insensitive to the ratio of iron to hydrogen in the plasma.

4.5. *Other Fits*

Optically thin modifications to blackbody emission depend on the emission process. Above we used free-free thermal bremsstrahlung. By replacing $\phi_{TB}(E)$ in Eq. 2 with thermal synchrotron ($\phi_{TS}(E)$), one obtains an optically thick/optically thin spectrum that is similar to TB-BB. Here

$$\phi_{TS}(E) = 1.75\times10^{-19} n_e l\ \Psi\ (m_ec^2/kT)^{1/2}\ e^{[-(4.5\ E/E_s)^{1/3}]} \qquad (4)$$

where $E_s = 11.6B_{12}(kT/m_ec^2)^2$ and B_{12} is the magnetic field in units of 10^{12} Gauss (*cf* Liang, Jernigan, and Rodrigues 1983). The curve labelled TS-BB in

Fig. 8 is a best fit for self absorbed thermal synchrotron. The best fit E_s is ~ 0.20 keV, comparable to the value found for the March fifth event (0.30 keV, Liang 1986). The Rayleigh-Jeans portion of $\phi_{BB}(E)$ is insensitive to the temperature so the temperature is not found independently by fitting Eq. 2 to the data, only BT^2 is constrained. However, we do assume that the emission is well above the first cyclotron harmonic so B_{12} should be less than ~ 0.5. Thus, the temperature must be at least ~ 30 keV. The temperature cannot be arbitrarily high since that would make the magnetic field so low that it could not counteract the super Eddington radiation pressure (see section 6.1). Ignoring the problem of confining the plasma and only addressing the assumptions behind Eq. 4, the temperature could easily be as large as 100 keV. The values of the other fit parameters depend on the temperature: $\Psi = 4.0(60\text{keV}/kT)$ km^2 kpc^{-2} and $n_e l = 2.9 \times 10^{22}(60\text{keV}/kT)^{-3/2}$ cm^{-2}. The TS-BB fit gives an unacceptable χ^2 (24 with 8 degrees of freedom) but due almost entirely to the SC data: the data above 15 keV bends more than allowed by Eq. 4. Liang (1987) has proposed that injected electrons that cool could explain the spectrum of SGR1806-20. The cooling electrons tend to have more curvature above 15 keV and, if the cyclotron fundamental is substantially below 15 keV, self absorption could explain the rollover. Liang compared such a model to GB790107. Above 15 keV there was general agreement although below 15 keV there was insufficient statistics to detect the rollover. In a future paper we plan to fit such models to the strong SGR events.

Mechanisms can produce a low energy rollover if the emission process has a low energy cut off. For example, thermal cyclotron is the sum of harmonically spaced, Doppler broadened emission. As such, below the first harmonic there is little emission, and the spectral shape at low energies is dominated by Doppler broadening. The position of the peak is set by the magnetic field and the emission

below the peak would fall very rapidly if the temperature parallel to the field is small. Norris *et al.* (1991) argues in favor of such a process. The relative emission at each harmonic can be calculated if one assumes an electron distribution among the Landau levels (*e.g.,* Brainerd and Lamb, 1987). In fact, the Brainerd and Lamb formulation gives an unacceptable χ^2; it predicts too much high energy emission. However, it is unclear how any electron distribution is maintained when the deexcitation timescale (10^{-15} sec) is so much faster than the collisional timescale. Brainerd (1989) has suggested that radiative excitation might populate the first excited state. However, a single gaussian is inconsistent with the data; it predicts too little high energy emission. Presumably, radiative excitation can populate several Landau levels (Norris *et al.*). We have fit two harmonically spaced gaussians allowing the scale factor between the first and second harmonic to be a free parameter (see "Gauss" in Fig. 8). That scale factor is related to the relative populations of the Landau levels. The best fit magnetic field is 1.5×10^{12} Gauss and the Doppler widths are the order of 15 keV. The fit is acceptable with a χ^2 of 2.5 with 6 degrees of freedom. However, there are five free parameters so it is not too surprising that there is an acceptable fit.

Various Comptonized spectra were tried. A Wien peak (saturated Compton, $\phi(E) = E^2\ e^{(-E/E_0)}$) fits poorly yielding a χ^2 of 25.4 with 9 degrees of freedom. Partially saturated Comptonization of a low energy source can be characterized by the energy of the injected photons (E_i), the temperature of the scattering medium (kT_s), and a parameter related to the optical depth. Here we have implemented the formulation of Sunyaev and Titarchuk (1980). The curve labelled "Com-I" in Fig. 8 used $E_i \sim 1$ keV and gave 8 keV for the best fit temperature of the scattering medium. The Sunyaev and Titarchuk γ parameter was 0.02. The fit was unacceptable with $\chi^2 = 35$ for 8 degrees of freedom. We also allowed the

injected spectrum to be a blackbody with the temperature a free parameter (see curve 'Com-BB" in Fig. 8). The best fit parameters were $kT_s = 10$, $\gamma = 0.64$, and the temperature of the injected blackbody was 5.5 keV. This fit gave an acceptable χ^2 (10 with 7 degrees of freedom) although there is a clear trend below the peak. In general, Comptonized spectra fit poorly because the observations imply a peak that is narrower than achievable with most Comptonization models.

The spectra of x-ray accreting pulsars are often represented as

$$\phi_{AccPul}(E) = E^{\alpha-1} \qquad E < E_c$$

$$= E^{\alpha-1} e^{(E_c - E)/E_F} \qquad E > E_c \tag{5}$$

(see White, Swank, and Holt 1983). This formulation is not directly derived from a physical model but gives an adequate representation of the accreting pulsar spectrum. The spectra of SGR1806-20 is similar to some accreting pulsars above ~ 15 keV but the accreting pulsars do not show a low energy rollover as strong as seen in SGR1806-20. Although SGR's and accreting sources may possibly occur near the surface and involve cyclotron processes, the super Eddington physics involved with an SGR is probably different than that associated with objects that are just at the Eddington limit.

The cyclotron up-scattering process (CUSP, Ho, Epstein, and Fenimore 1992, Dermer and Vitello, 1992) produces spectra that have a low energy rollover at the temperature of the underlying source of photons and a high energy rollover at B^2/kT. If $B \sim kT$ then CUSP can produce a single peak. Such a function fits poorly because the shape of the emission below the peak has a Doppler half-width equal roughly to the temperature and it was too broad to give an acceptable fit.

5. BURST INTENSITIES

Table I summarizes the burst intensities for the four strongest events defined by the sum of their counts in SC1 and SC2. The fluxes are dependent on the durations of the events which are available from Kouveliotou *et al.* (1987) and Atteia *et al.* (1987). Previous work reported peak fluxes only for emission above 30 keV. Our peak energy flux (for above 30 keV) is found by integrating the best fit function for TB-PE above 30 keV (see Table II, Fig. 2). The peak energy fluxes agree, on the average, with those of Kouveliotou *et al.* and Atteia *et al.* to within 10%. The spectra fall off rapidly both below 15 keV and above 50 keV. Thus, the total flux can be estimated by integrating the best fit TB-PE function over all energies (*e.g.,* 5.3×10^{-5} erg cm^{-2} sec^{-1} for the brightest event, Table I). About 2/3 of the total flux comes from below 30 keV. Kulkarni and Frail (1993) suggested that G10.0-0.3, a supernova remnant at 17 kpc, is associated with SGR1806-20 and Murakami *et al.* (1994) has observed a SGR1806-20 event centered on the remnant. Using this distance one can estimate the total luminosity of the events. The brightest ICE events had a luminosity of 1.8×10^{42} erg sec^{-1}, about 2×10^{4} times the Eddington limit. Although that is extremely luminous, the March fifth event was a factor of 450 times more luminous (above 30 keV). In the bandpass of 5 to 50 keV, the brightest SGR1806-20 event rose to 300 Crab and turned off again within ~ 0.1 sec.

6. DISCUSSION

6.1. *Super Eddington Fluxes in a Magnetic Field*

The identification of SGR1806-20 with the supernova remnant G10.0-0.3 has given us a distance (~ 17 kpc) and therefore a total luminosity which peaks at $\sim 2\times 10^{42}$ erg sec^{-1} (see Table I). The Eddington Limit, L_E, is the maximum luminosity

where the radiation pressure does not exceed the gravitation force. Simplistically,

$$L_E \sim \frac{4\pi G M m_H c}{\sigma_{Th}} \sim 10^{38} \quad \mathrm{erg} \quad \mathrm{sec}^{-1} \tag{6}$$

where G is the gravitational constant, M is the mass of the star, m_H is the mass of a proton, c is the speed of light, and σ_{Th} is the Thompson cross section. SGR1806-20 has produced events that are $\sim 2 \times 10^4$ times the Eddington Limit. The SGR super Eddington fluxes can last from 100 ms to 200 sec, much longer than the dynamic time scale of a neutron star. Such a super Eddington flux makes accretion models unlikely (although not all authors would agree, see *e.g.,* Colgate and Leonard, 1993). The initial angular momentum of an accreting body and tidal forces would likely break up a body such that it is susceptible to radiation pressure. Some explanations have depended on the magnetic field to either confine the plasma and/or reduce the opacity such that the radiation cannot blow the accreting material away. The magnetic field falls off rapidly (R^{-3}) but the Eddington Limit is independent of radius so it seems unlikely that magnetic field effects will allow accretion with typical impact parameters to be sustained for many dynamic timescales in the presence of a super Eddington flux.

We favor an internal (yet unspecified) source of energy. The super Eddington flux is still a concern for internal sources since the pressure should blow away the energy producing material. However, at the surface the magnetic field can modify the Eddington limit in two ways. The field might be able to provide a geometery-dependent confining pressure (Lamb 1982) or a super strong magnetic field ($\sim 10^{14}$ Gauss) can reduce the opacity at low energy where the SGRs radiate (Paczyński 1992).

First we consider the effect of the magnetic field on the opacity. At energies

much less than the cyclotron fundamental, E_{cyc}, the Compton cross section follows

$$\sigma_{cyc,1} \approx \sigma_{Th}\left(\sin^2\theta + \cos^2\theta (E/E_{cyc})^2 \right)$$

$$\sigma_{cyc,2} \approx \sigma_{Th}(E/E_{cyc})^2 \tag{7}$$

where $\sigma_{cyc,1}$ and $\sigma_{cyc,2}$ are for the two linear polarization states and θ is the angle of the photon relative to the magnetic field (Herold 1979). Paczyński (1992) suggested that the Rosseland mean opacity be used in Eq. 6. The Rosseland mean gives the most weight to the lowest opacity and could reflect how the radiation evolves to escape along the opacity windows of least resistance. For unpolarized light the lowest opacity is along the field lines and it is unlikely that the geometry is such that we are always looking along the field lines. (We see many bursts from 1806-20 and sustained pulsations from the SGR phase of the March 5 event.) The flux-weighted mean should be used in Eq. 6 (see *e.g.*, Mihalas 1970). The Eddington Limit in the presence of a super strong magnetic field, $L_{E,B}$, is

$$L_{E,B} = L_E \frac{\int_0^\infty \sigma_{Th} E\phi(E)dE}{\int_0^\infty \sigma_{cyc} E\phi(E)dE} \tag{8}$$

if $\phi(E)$ is effectively zero for $E \gtrsim E_{cyc}$. Note that, here, the observed spectrum is used (*cf.* Eqs. 1-5). Let ψ_1 be the fraction of the radiation that is in linear polarization state 1, and $\psi_2 = 1 - \psi_1$ then

$$\frac{L_{E,B}}{L_E} = \frac{\int_0^\infty E\phi(E)dE}{\psi_1 \int_0^\infty \left(\sin^2\theta + \cos^2\theta (\frac{E}{E_{cyc}})^2\right) E\phi(E)dE + \psi_2 \int_0^\infty (\frac{E}{E_{cyc}})^2 E\phi(E)dE} \tag{9}$$

For unpolarized light, the Rosseland mean gives a large $L_{E,B}$ whereas the flux-weighted mean gives $L_{E,B} \sim L_E(\psi_1 \sin^2\theta)^{-1}$ where $\psi_1 \sin^2\theta$ is the order of unity. Thus, we suggest that in order to have $L_{E,B} \sim 10^4 L_E$ (as required by the observations), ψ_1 must be the order of 10^{-4}; the radiation must be completely

polarized. Perhaps the polarization state evolves until all of the radiation is in the polarization state that can escape.

Our observations could completely define $\phi(E)$ since it falls off rapidly at both high and low energy. Significant unmeasured emission below our lowest observation ($\sim$ 5 keV) would not affect Eq. 9. Unmeasured emission above our highest observation ($\sim$ 1.2 MeV) is unlikely. We can evaluate Eq. 9 for the various spectral shapes that give acceptable fits to the data and determine the minimum E_{cyc} that gives $L_{E,B} = 2 \times 10^4 L_E$. The resulting E_{cyc}'s vary from 4700 keV for the two gaussian fit to 5700 keV for the BB-TB fit. The corresponding magnetic fields are the order of $4 - 5 \times 10^{14}$ Gauss. This is the same value as obtained by Paczyński except we require that the radiation be completely polarized and we have some confidence that $\phi(E)$ is completely known.

Alternatively, the magnetic field can exert a pressure which assists the gravitational forces in retaining the plasma near the surface. The confining forces depend on the geometry and it is not clear if the plasma can be confined on open field lines such as might be found near the poles. Lamb (1982) suggested that the field necessary to confine the plasma can be found from

$$\beta \frac{4\sigma T^4}{c} \ll \frac{B^2}{8\pi} \tag{10}$$

where σ is the Stefan-Boltzmann constant and β depends on the angular distribution of the radiation field; it is 1/3 for isotropic radiation. Here, we have required that the magnetic field energy density be much larger than the radiation pressure since the magnetic field does not confine the plasma along the field lines. From Eq. 10, the requisite magnetic field can be estimated

$$B_{12} \gg \left[\frac{T}{170}\right]^2 \tag{11}$$

where T is in keV. For example, Norris *et al.* used 30 keV implying a field of $B_{12} \sim 0.03$. This estimate is valid only if the process is blackbody. A lower limit on the requisite field can be found from the radiation pressure on the outer photosphere, that is, the region where the observed spectrum is formed (*cf.* Fenimore, Klebesadel, and Laros 1984):

$$B^2 \gg \beta \frac{32\pi}{c} \left(\frac{D}{R}\right)^2 \int_0^\infty E\phi(E)dE. \tag{12}$$

Here, D is the distance and R is the radius of the source. Substituting standard values gives

$$B_{12} \gg (D/\mathrm{kpc})(R/\mathrm{km})^{-1} I_{total}^{1/2}. \tag{13}$$

This expression is very useful since it depends only on the observed intensity and does not make the assumption that the process is blackbody. From Table I, I_{total} is 5.3×10^{-5} erg sec^{-1} cm^{-2} and using $D = 17$ and $R = 10$, gives $B_{12} = 0.012$.

In comparing estimates of the magnetic field from Eqs. 11 and 13, one should note that Eq. 11 uses the observations to determine the temperature and does not require knowledge of the distance or the radius of the source. However, Eq. 11 assumes that the shape of the spectrum (and the process generating the photons) is equivalent to a blackbody. Our fits involved "temperatures" that varied by an order of magnitude from 9 keV for a blackbody to $\sim$ 100 keV for self absorbed thermal synchrotron requiring fields of $B_{12} = 0.003$ to 0.3. Equation 13 uses the observations to determine the shape of the spectrum and is useful if some estimate of the distance and radius is possible. Eq. 13 only limits the outer photosphere and deeper in the photosphere the spectrum might be closer to blackbody with the temperature that characterizes the optically thin observed emission making Eq. 11 more appropriate. This is uncertain since we do not know the process that generates the observed spectrum nor if it ever takes on the characteristics of a blackbody deeper in the

photosphere. For example, there could be an electron acceleration process that produces an maxwellian velocity distribution with a particular temperature but the radiation field may not come into equilibrium with it. In that case, Eq. 13 would be more appropriate to use. Equation 13 is a lower limit and in most cases (SGRs, x-ray bursts, classic gamma-ray bursts) we have fairly good estimates of I_{total} although not always D and R. Equation 11 requires the temperature and that is model dependent. In either case, whether the field can truly confine the plasma through magnetic pressure depends on the geometry of the field lines.

6.2. *The Role of the Magnetic Field in the Emission Process*

There is general agreement that the magnetic field plays a crucial role in the SGR phenomenon (Laros *et al.* 1986, 1987, Liang 1987, Norris *et al.* 1991, Paczyński 1992, Colgate and Leonard 1993). The range of fields that have been suggested spans nearly a factor of $\sim 10^4$. Here we discuss these suggestions in the context of our spectral observations.

A very strong field ($\sim 5 \times 10^{14}$ Gauss) suppresses the opacity and allows a super Eddington flux (Paczyński 1992). If that is the case, then the two-gaussian fits and the self-absorbed synchrotron fits are irrelevant since they require much smaller fields. The remaining potential process that can produce the continuum is thermal bremsstrahlung. Self-absorbed thermal bremsstrahlung requires a large photosphere ($\Psi \sim 30$ km^{2}kpc^{-2}, radius ~ 50 km, see Table I) which would require a surface field of $\sim 6 \times 10^{16}$ Gauss, probably an unreasonable value for a 10 km radius surface. Thus, the large field assumption might be one way to explain the macroscopic issue of the super Eddington flux but the process generating the photons is still unclear. Whatever the process is, it must be capable of producing 100% polarized radiation, take place near the surface, and operate well below the cyclotron fundamental. One

possible process is to consider that the electrons are always in the ground Landau state such that they act as beads on strings. The relative motions follow an one-dimensional maxwellian and the electrons radiate in a manner similar to free-free bremsstrahlung.

The two gaussian fit could be evidence that the process is low harmonic emission from a magnetic field of $\sim 2 \times 10^{12}$ Gauss (Norris, *et al.* 1991). The low energy cutoff is then related to the Doppler width of the first harmonic, that is, the parallel temperature of the emitting electrons. It is unclear how the excited Landau levels remain populated. A 2×10^{12} Gauss field would not reduce the opacity sufficiently to allow the super Eddington flux so the super Eddington flux must be counteracted by magnetic field pressure.

A low field ($\sim 10^{11}$ Gauss) might be able to explain the observed continuum through self absorbed synchrotron radiation (Liang 1986, Liang 1987). Either thermal or injected electrons radiate in high harmonics but merge into the Rayleigh-Jeans continuum at $\sim$ 15 keV. The surface area ($\Psi \sim 4$ km^2 kpc^{-2}, radius $\sim$ 10 km) is reasonable. The assumption that the first harmonic is at a lower energy than where the emission is self absorbed requires the magnetic field to be less than $\sim 5 \times 10^{11}$ Gauss. Equation 11 (which limits BT^{-2}) combined with the E_s value of 0.2 keV (which limits BT^2) requires the field to be much larger than 1.2×10^{11} Gauss. Thus, the field required for self absorbed thermal synchotron might be too small to confine the plasma against the super Eddington flux. Only the lower limit from Eq. 13 (1.2×10^{10} Gauss) is consistent with both confining the plasma and generating the spectrum.

6.3. *The Nature of the Low-Energy Rollover*

We have presented three different explanations for the low energy rollover seen

in SGR1806-20: the Doppler broadened emission from cyclotron line emission, self-absorption by either thermal or synchrotron processes, or absorption by circumstellar material. The two-gaussian fit is the best evidence for the Doppler broadened emission explanation and more work will be necessary to develop a complete model of this process. It might have the advantage that it could explain the fact that the spectrum seems identical for events that vary in intensity by a factor of 50. The spectra would be very similar if the ratio of emission in the second harmonic compared to the first is set by relative probabilities of transitions involving two Landau levels to that involving one.

Photoelectric absorption by neutral material requires a column density of 10^{24} Hydrogen atoms cm^{-2}. Such a high column density is rarely found except in the cores of extremely dense molecular clouds. Figure 5 of Sanders *et al.* (1986) does not show dense molecular clouds in the direction of SGR1806-20 so we conclude that, if photoelectric absorption is involved, it is due to circumstellar material. This material cannot be close to the origin of the bursts since the iron would be completely ionized by the radiation (see section 4.4). The material must be a few A.U. away from the source. Assuming spherical symmetry, the amount of material is quite large: $\sim 4\pi R_a^2 \zeta N_H$ or $\sim 2 \times 10^{-6} \zeta M_\odot (R/\mathrm{A.U.})^2$ where ζ is the ratio of the amount of iron in the plasma to what one would expect with a cosmic abundance. If the circumstellar material extends closer to the central source, then weak bursts would ionize it less than strong bursts resulting in a correlation between intensity and low energy emission: weaker bursts would have less low energy emission. Although the uncertainties are large, Fig. 7 tends to show the opposite, that the emission below the peak tends to be more for weaker bursts. Thus, there is no reason to suspect that the absorbing material is close to the central source thereby reducing the amount of material necessary: R_a could be larger than a few

A.U. requiring between 10^{-5} and $10^{-4}\zeta M_\odot$ of material. However, ζ could be quite small if the material is very iron rich.

Murakami *et al.* (1994) has suggested that a steady source observed by Asca (AX1805.7-2025) is also the origin of the SGR1806-20 events. The steady source has a spectrum that is absorbed by neutral material but with a column density of only $10^{22} N_H$ cm^{-2}. If the steady source is also the SGR source then the rollover is probably not due to absorption by neutral material since it is unlikely that the column density due to material a few A.U. from the source would change by two orders of magnitude. Independent of the cause of the low-energy roll over we report in this paper, it appears likely that the steady source seen by Asca is not the SGR1806-20 source but is the plerion itself acting as a foreground object. Then the $10^{22} N_H$ cm^{-2} reported by Murakami *et al.* is best explained as the typical interstellar absorption in this direction. The actual SGR source would be buried deeper in the plerion and have a substantial amount of circumstellar material causing the low energy rollover we observe. In fact, if the roll over is due to $10^{24} N_H$ cm^{2}, then any typical steady emission from the neutron star would be hidden from most instrumentation. The strongest argument against the low energy rollover being due to neutral absorption is the rather large amount of material that would be required.

Self absorption could arise from either thermal or synchrotron processes. A completely optically thick spectrum (*i.e.,* a blackbody spectrum) does not seem to give an acceptable fit (Table II). However, an optically thin/optically thick thermal bremsstrahlung spectrum assumes some self-absorption and can give an acceptable fit (see Table II). Although optically thin/optically thick synchrotron did not fit as well (see section 4.5), more detailed calculations involving injected electrons or cooling distributions (*cf.* Liang 1987) might be able to fit. For free-free self

absorption, $n_e^2 l$ is 1.1×10^{51} cm^{-5}. The assumption of being optically thin implies that $\sigma_{Th} n_e l$ is less than unity so $l \sim 10^{-3}$. The very thin regions required by free-free emission is an argument against thermal bremsstrahlung as the process producing the photons. For self absorbed thermal synchotron, $n_e l$ is 2.9×10^{22} so it is self consistent with the assumption of being optically thin and there are no constraints on the thickness of the emitting region.

The spectrum above the peak is remarkably similar implying a constant temperature yet the intensity varies by a factor of 50. This implies that the area is the only parameter that changes from burst to burst. This is very unlike other transient events thought to occur on neutron stars (such as Type I x-ray bursts) that usually have a somewhat constant temperature but varying emitting area. Using the distance to G10.0-0.3 and the Ψ parameter for the brightest events, the maximum size of the emitting region has a radius of $\sim$ 50 km for the TB-BB fit and $\sim$ 10 km for the TS-BB fit, a more reasonable value for a neutron star. The emission is probably near the surface for two reasons: (1) it was near the surface during the SGR phase of the March 5th event (the pulsations) and (2) if one uses the magnetic field to confine the plasma against the super Eddington flux, then the surface is the best place to do that since the magnetic field falls off as R^{-3} whereas the Eddington flux is independent of distance.

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FIGURE CAPTIONS

Fig. 1: Hardness Ratios for 95 SGR1806-20 events seen by ICE as a function of fluence. Hardness is the ratio of the 43.2 to 77.5 keV energy channel to the 25.9 to 43.2 channel. The solid line is a best fit linear function. There is very little variation over a dynamic range of 50 implying that only the emitting area is changing from burst to burst.

Fig. 2: Different spectral fits to the sum of the largest and third largest SGR1806-20 event. BB is blackbody, TB-BB is optically thin thermal bremsstrahlung merged into a blackbody, TP-PL is thermal bremsstrahlung connected to a power law, and TB-PE is thermal bremsstrahlung with photoelectric absorption by $\sim 10^{24}$ Hydrogen atoms cm^{-2} with a cosmic abundance.

Fig. 3: Same as Fig. 2 except for the second strongest SGR1806-20 event.

Fig. 4: Same as Fig. 2 except for the fourth strongest SGR1806-20 event.

Fig. 5: Same as Fig. 2 except for the sum of the first four strongest SGR1806-20 events.

Fig. 6: Same as Fig. 2 except for the sum of the 5^{th} to the 14^{th} strongest SGR1806-20 events.

Fig. 7: Same as Fig. 2 except for the sum of the 15^{th} to the 40^{th} brightest SGR1806-20 events.

Fig. 8: Spectral fits to the largest and third largest SGR1806-20 events. TS-BB is an optically thick/optically thin spectrum based on thermal synchrotron, Gauss is the sum of two Gaussians, Wien is a saturated Comptonized spectrum, Com-In is Comptonization of soft injected photons, Com-BB is a Comptonized blackbody, and ACC PUL is an accreting pulsar spectrum.

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